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# Statistical Analysis of CFD Results for Missile Surface Pressures

by Walter B. Sturek, Sr. and Malcolm S. Taylor

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## Abstract

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An international computational aerodynamics study under the auspices of The Technical Cooperation Program (TTCP) Weapons Technology Panel 2 (APN-TP-2) involving participants from defense research laboratories of the United States, United Kingdom, Canada, and Australia was recently completed. The purpose of this study was to examine computational predictive technologies for finned missile shapes by comparing Navier-Stokes predictions to experimental data. Experimental data consisting of surface pressures on the body and fins, flow field pitot pressures, and force measurements were available for comparison to the computational results. The computational results for this study established an extensive database for evaluation and comparison. The full database consists of results from six Navier-Stokes codes obtained by seven multi-block patched and unstructured grids for five distinct test cases. The statistical analysis techniques developed to help provide an evaluation of the predictive techniques are described. Quantitative results of the analysis of the differences between computational and experimental results are presented graphically and quantitatively in terms of medians, standard deviation, and a figure of merit to assist in the overall evaluation of the study results. The good performance achieved using the Spalart-Allmaras turbulence model and multi-block patched and unstructured grid techniques are noted in the findings.

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## Abstract

An international computational aerodynamics study under the auspices of The Technical Cooperation Program (TTCP) Weapons Technology Panel 2 (WPN-TP-2) involving participants from defense research laboratories of the United States, United Kingdom, Canada, and Australia was recently completed. The purpose of this study was to examine computational predictive technologies for finned missile shapes by comparing Navier-Stokes predictions to experimental data. Experimental data consisting of surface pressures on the body and fins, flow field pitot pressures, and force measurements were available for comparison to the computational results. The computational results for this study established an extensive database for evaluation and comparison. The full database consists of results from six Navier-Stokes codes obtained by seven participants, seven turbulence models, and structured, multi-block patched and unstructured grids for five distinct test cases. The statistical analysis techniques developed to help provide an evaluation of the predictive techniques are described. Quantitative results of the analysis of the differences between computational and experimental results are presented graphically and quantitatively in terms of medians, standard deviation, and a figure of merit to assist in the overall evaluation of the study results. The good performance achieved using the Spalart-Allmaras turbulence model and multi-block patched and unstructured grid techniques are noted in the findings.

## Introduction

An international computational aerodynamics study was recently completed under the auspices of The Technical Cooperation Program (TTCP) Weapons Technology Panel 2 (WPN-TP-2). It involved participants from defense research laboratories of the United States, United Kingdom, Canada, and Australia was recently completed. This current study follows a previous study on an ogive-cylinder body<sup>1,2,3</sup> which was reported earlier. The purpose of

this study was to examine computational predictive technologies for finned missile shapes by comparison of Navier-Stokes predictions to experimental data. Experimental data consisting of surface pressures on the body and fins, flow field pitot pressures, and force measurements were available for comparison to the computational results. The computational results for this study have established an extensive database for evaluation and comparison. This database consists of results from six Navier-Stokes codes by seven participants, seven turbulence models, and structured, multi-block patched and unstructured grids for five distinct test cases. The statistical analysis techniques developed to help provide an evaluation of the predictive techniques are described. Quantitative results of the analysis of the differences between computational and experimental results are presented graphically and quantitatively in terms of medians, standard deviation, and a figure of merit to assist in the overall evaluation of the study results. The full scope of the computational study resulted in a large number of test-case results for evaluation with respect to each other and to the effects of grid resolution, choice of turbulence model, and computational technique. For the purpose of this paper, a subset of the full study was selected for analysis. The analysis reported here considers surface pressure results for two test cases for a finned missile at Mach 2.5 and 14° angle of attack.

## Model and Experimental Data

The experimental model for the results considered in this paper is shown in Figure 1 mounted in the wind tunnel at NASA Langley Research Center. This model has a 3-cal. ogive nose followed by a cylindrical section of 12-cal. length. Four delta fins are located on the aft portion of the cylinder starting at  $x/d = 6.639$  and ending at  $x/d = 10.013$ . The leading edge sweep angle of the fins is 18.435°. A computed visualization<sup>5</sup> of the flow over

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the model at Mach = 2.5,  $\alpha = 14^\circ$  is shown in Figure 2. Pitot pressure contours are shown at selected axial stations. The substantial flow separation is clearly evident in the developing vortex structures evolving from the leading edge of the nose and the fins. Obviously, this is a very challenging test case for computational techniques.

Experimental data in the form of surface pressures, pitot pressures in the outer flow field and strain gage force and moment measurements are available to compare with the computational results<sup>4</sup>. The layout of the surface pressure taps on the cylindrical body and fins is shown in Figure 3. During the measurements, the model was rolled in increments to permit measurements for the full circumferential extent of the flow field. For the analysis discussed in this paper, only surface pressure measurements at selected locations on the cylindrical body and fins were utilized. The positions selected for the cylindrical body were  $x/d = 5.5, 7.927, 8.788$  and  $9.937$ . Referring to Figure 3, the fin pressures selected were identified as rows a, c, e, and g.

An example of calculations for surface pressure compared to experimental data<sup>5</sup> is shown in Figure 4 at  $x/d = 5.5$  for the: Spalart-Allmaras(SA), Baldwin-Barth(BB), and Baldwin-Lomax(BL) turbulence models. The SA results pick up the first suction peak very well, but the second suction peak and lee side separated flow are less well defined. Results for all three turbulence models have good agreement on the wind side and at the pitch plane of symmetry. The difference between calculation and experiment for these same data is shown in Figure 5. As expected, the difference between calculation and experiment is very small on the wind side; however, the difference is quite pronounced for the lee side separated flow. These data (difference between experiment and computation) are operated on by the statistical analysis technique described in the next section to develop the statistical results.

In the discussion that follows, many references are made to the various data sets using a short hand notation. This notation is shown in Tables 1 and 2 where the CFD codes and turbulence models used in this study are listed.

### **Statistical Methodology**

The wide availability of powerful and affordable computing resources has impacted the way in which data analysis is conducted at a fundamental level.

expressions such as data mining, exploratory data analysis, and data visualization have entered the lexicon. A basic tenet is that data, properly summarized and effectively portrayed, may speak directly to the subject-matter expert without resort to extensive or arcane statistical methodology.

A set of experimental data serves as a baseline for comparison of the flowfield predictors. The technique involves the comparison of two data sets: a set of experimental data and a set of computed results. To facilitate discussion, the experimental data are denoted as  $Y_{ij}^{kl}$ .

The subscripts  $(i, j)$  identify the location of the pressure measurements on the projectile. For the body,  $i = 5.5, 7.93, 8.79, 9.94$  specifies the axial station and  $0 \leq j \leq 360^\circ$  in the circumferential position. For the fins,  $(i, j)$  are the usual Cartesian coordinates (Figure 3). The superscripts  $(k, l)$  distinguish subsets of the experimental data:  $k = 1$  corresponds to the body and  $k = 2$  the fins;  $l = 1$  corresponds to  $0^\circ$  roll angle (a.k.a. + - configuration) and  $l = 2$  to  $45^\circ$  roll angle (a.k.a. x-configuration). The corresponding computed values are denoted as

$X_{ij}^{kl}$ , where the subscripts and superscripts perform the same role for the experimental data. If the difference between a computed value of surface pressure and the corresponding experimental measurement is defined as error, then  $E_{ij}^{kl} = Y_{ij}^{kl} -$

$X_{ij}^{kl}$  is the error at location  $(i, j)$  for data set  $(k, l)$ .

Reduction of the subsets of pressure differences must be accomplished before a simultaneous comparison of flow field calculations can be effectively undertaken. Toward this end, a box and whisker plot is a useful device for data visualization, Figure 6. To construct a box and whisker plot for a data set  $\{E_{ij}^{kl}\}$ , the errors are first ordered from smallest to largest. The bottom and top of the box are the 25th and 75th percentiles, respectively, of the ranked errors; the median, or 50<sup>th</sup> percentile, is represented by the line approximately midway within the box. The whiskers are the lines that emanate from the box and extend toward the extreme values of the data set. A value between 1.5- and 3h above the upper box limit (75<sup>th</sup> percentile) is designated as an *outlier*, and values in excess of 3h, an *extreme value*. An entirely analogous statement holds for values below the lower box limit (25<sup>th</sup> percentile). Figure 6 provides a compact description of how the values within a subset are distributed, facilitating

comparison across several sets of data. The designation of certain points as outliers or extreme values is an attempt to maintain graphic fidelity while avoiding undue, and possibly misleading, extension of whisker lengths caused by only a few values. Outliers and extreme values are usually the object of close scrutiny by data analysts to verify their authenticity and to exclude the possibility of their resulting from some type of spurious behavior.

If the computed and experimental values coincide at every location ( $i, j$ ), the box and whisker plot will collapse to a single value--zero. Failing that, a thin box with short whiskers indicates good overall agreement. For example, inspection of Fig. 7a suggests that data sets [SA(H)] and [PDT(L)] may be closest to this ideal.

The statistical graphics in Figures 7-8, although enlightening, suggestive, and highly appropriate for an initial screening, still do not provide a quantitative assessment of which error sets represent closest agreement between experiment and computation. Clearly, we would like the errors to be tightly clustered about zero. Such a distribution of errors would be reflected in a location parameter (a mean or median) and a dispersion parameter (a standard deviation or interquartile range), assuming values close to zero, Figure 9. An attempt to formally rank the effectiveness of the computation procedures, as revealed through the error sets should involve a statistic that includes measures of both location and dispersion.

For this purpose, as a statistic we chose the distance between the point determined by the sample median and standard deviation, denoted as ( $m, s$ ), and the origin (0,0). Notice that the origin corresponds to perfect agreement between calculation and experiment, so the closer ( $m, s$ ) is to the origin, the better the agreement.

The distances  $\sqrt{m^2 + s^2}$  were determined for the body + fins results for roll = 0 and roll = 45°. These results are presented in Tables 3 and 4 in rank order with the closest agreement listed first.

More complicated ranking procedures are possible, but to engage in them without a compelling reason serves no practical purpose and was not undertaken.

The results of the ranking procedure are entirely consistent with the preliminary graphics. For the

statistician, failure to account for error in the experimental measurements  $Y_{ij}^{kl}$  is troublesome, but engineering experience leaves the subject-matter expert convinced that concern over this point is unwarranted. In this study, only a single set of experimental data is available. All of the flow field predictors are deterministic, and the measurement error, whatever its magnitude, remains confounded with the recorded observations.

## Discussion of Results

The results for roll = 0 are shown in Figures 7a, 7b, and 7c. The appearance of the outliers indicates the consistency of the results. The outliers could be caused by turbulence model effects and/or deficiencies in the computational grid. This information would provide the computational specialist incentive to reevaluate his results in these areas. In considering the variety of turbulence models, CFD codes, and grid configurations, it is informative to consider the results in similar groupings.

First, consider the structured grid results for body alone. These results are represented by the following ID's: SA(H), BB(H), BL(H), BL10(H), SST(H), PW(S), SA(D), BL(L), PDT(L), SA(TB). One observation is that the results using the BL turbulence model have the greatest presence of outliers. The results using SA turbulence model appear to be more consistent than others, yielding no extreme values. The SST and PDT turbulence models also provide encouraging results. For the unstructured grid results [ID's: SA(K), SA(B)], the presence of outliers is greater than for the results using the same turbulence model with structured grids.

The results for fins are shown in Figure 7b. Noteworthy here are the results for PW(S) and SA(D). These results were obtained using the same structured grid and they have no extreme values. These results are better than they achieved for the body alone. The results achieved using the SA turbulence model appear to be consistently better than that for other turbulence models. One exception is the SA(K) result which has several extreme values. Time did not permit close examination of these data to ensure that the data reduction technique did not introduce some errors when interpolating the irregular, unstructured data to the regular grid of the experimental data.

The results for the body plus fins are shown in Figure 7c. These results are dominated by the fins and are quite similar to the results from Figure 7b.

The results for roll = 45 are shown in Figures 8a, 8b, and 8c. The results for body alone are very similar to the results for roll = 0. Again, the SA turbulence model results appear to be consistently somewhat better than results for other turbulence models. There is some indication that the fin results have a greater amount of outliers than the fin results for the roll = 0 case. Also, the PW(S) and SA(D) results, which were obtained using similar CFD codes and the same grid, are the only results with no extreme values.

The plots shown in Figures 9a and 9b indicate the relative rank ordering of the results in terms of the median and standard deviation. The result closest to the origin (0,0) would be the best. In Figure 9a, for roll = 0, the results indicate that the structured grids using SA turbulence model perform the best, although the results obtained using SST, PDT, and BB turbulence models also performed well. The results shown in Figure 9b for the roll = 45 case are similar. Tables 3 and 4 sort the tabulated results for these two figures from best to worst. The median values are consistently less than zero indicating that the computations are under predicting the surface pressures. This trend is also observed in Figure 4. The statistical data suggest that the roll = 0 case is slightly better predicted than the roll = 45 case. However, the differences are so slight that this may not be statistically significant. For both sets of data (Table 3 and Table 4), three of the top four results were obtained by Haroldsen<sup>5</sup>; his results were obtained using a structured, patched multi-block grid generation technique.

### **Concluding Remarks**

Traditionally, an engineer evaluates flow field computations by visual inspection and a qualitative comparison with experiment, an often satisfactory process for a small number of data sets. However, in this study, the number of data sets was sufficiently large to make the evaluation and comparison of the results an unwieldy task. Thus, a statistical approach, with emphasis on data visualization, was used to assist the engineer in comparing Navier-Stokes predictions to experimental measurements. The method was applied to a set of computational results obtained by seven participants using six CFD codes and seven turbulence models for a finned missile at Mach 2.5 and 14° angle of attack. The analysis showed that using more computer-intensive

turbulence models did not provide correspondingly superior results. It was also noted that the results obtained using unstructured grids were very competitive with those obtained using conventional structured grids. The statistical procedure developed for this study makes few assumptions; it is of particular value when comparing a large number of data sets and when an impartial quantitative assessment is desired.

### **Acknowledgements**

The authors wish to acknowledge the contributions of Fred Brundick (Army Research Laboratory) and Douglas Plotner (Mississippi State University) for their efforts in the process of sorting, filing and organizing the data sets for the analysis. The authors also wish to acknowledge the excellent cooperation of the participants listed in References 5-10 in making the results of their computations available for this analysis. We also would like to thank the National Leaders of the TTCP Weapons Technology Panel 2 for their support of this study which was chartered as KTA 2-15.

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**Table1. List of Navier-Stokes Codes Utilized**

Participant (Ref)	Identification	Code Name	Brief Description
Birch (8)	TB	FLUENT	FV, Implicit, structured
Bulbeck (6)	B	FLUENT	FV, Implicit, unstructured
Dinavahi	D	OVERFLOW	FV, Implicit, Upwind, structured
Haroldsen (5)	H	WIND 1.0	FV/FD, Implicit, multi-block
Kinsey (10)	K	COBALT	FV, Implicit, unstructured
Lesage (9)	L	WIND 1.0	FD, Implicit, structured
Sahu (7)	S	ZNSFLOW	FD, Implicit, Upwind, structured

**Table 2. List of Turbulence Models and Designation Code**

Code	Turbulence Model
BB	Baldwin-Barth
BL	Baldwin-Lomax
BL10	Baldwin-Lomax with limiter
PDT	PD Thomas
PW	Pointwise
SA	Spalart-Allmaras
SST	Shear Stress Transport

**Table 3. Ordered Figure of Merit for  
Body + Fins, Roll = 0**

ID	Median	Std Dev	Distance
SA(H)	-0.00044	0.013838	0.013845
SST(H)	-0.00159	0.01411	0.014199
PDT(L)	-0.00223	0.014433	0.014605
BB(H)	-0.00147	0.015115	0.015186
SA(TB)	-0.00096	0.016014	0.016042
BL(H)	-0.00182	0.016353	0.016454
BL(L)	-0.00201	0.016781	0.016901
SA(B)	-0.00217	0.017159	0.017295
PW(S)	-0.00198	0.018933	0.019035
SA(D)	0.003066	0.019456	0.019696
BL10(H)	-0.00274	0.021424	0.021599
SA(K)	-0.00231	0.023618	0.023731

**Table 4. Ordered Figure of Merit for  
Body + Fins, Roll = 45**

ID	Median	Std Dev	Distance
SA(H)	-0.00273	0.014409	0.014665
BL(H)	-0.00241	0.014777	0.014972
SA(TB)	-0.00272	0.014813	0.015061
BB(H)	-0.00274	0.015119	0.015366
PDT(L)	-0.00326	0.016432	0.016752
PW(S)	-0.00455	0.017157	0.017750
SA(D)	-0.00204	0.018871	0.018980
SA(B)	-0.00459	0.019283	0.019821
SA(K)	-0.00480	0.021708	0.022232

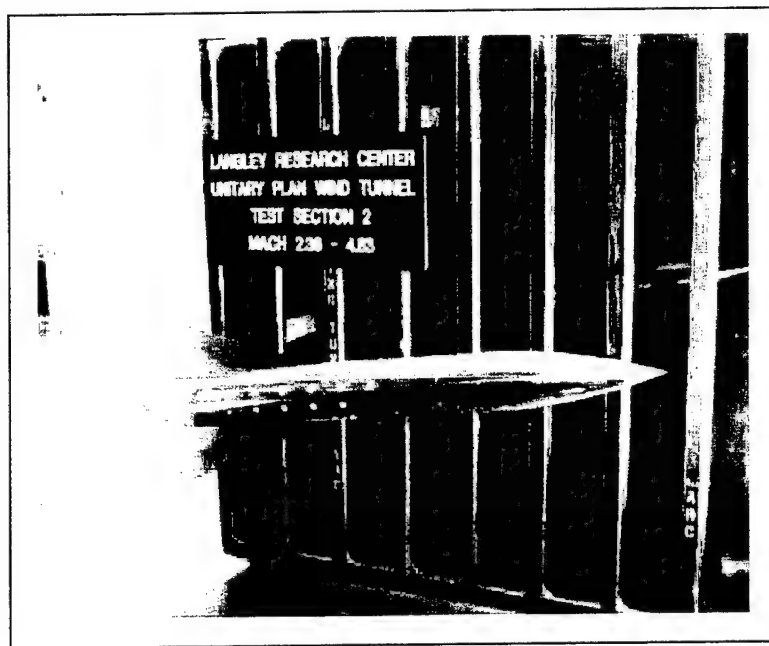


Figure 1. DERA Finned Model Mounted in NASA Langley Wind Tunnel

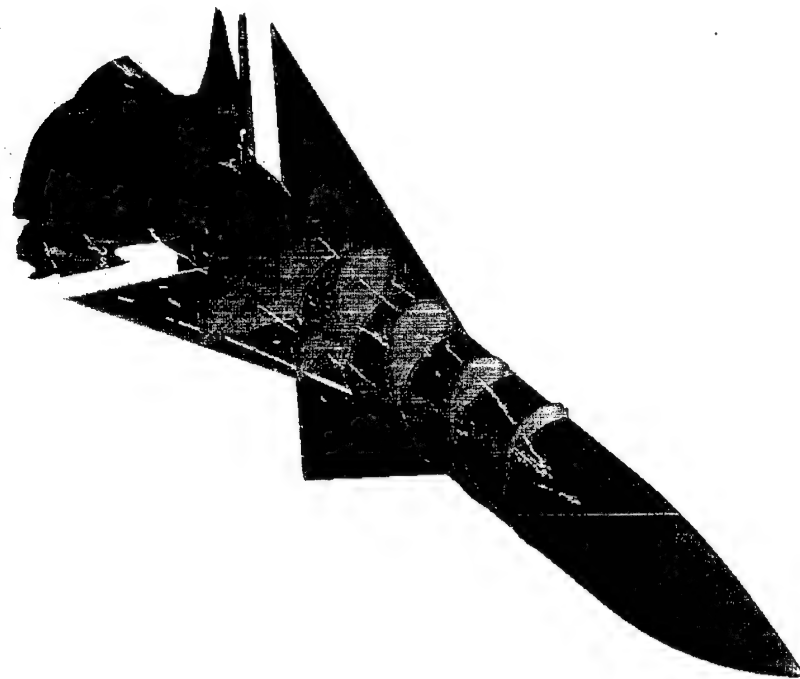


Figure 2. Visualization of Flow Over DERA Missile For  $M=2.5$ ,  $\alpha = 14^\circ$ ,  $\text{Roll} = 0$ , Pitot Pressure Contours.

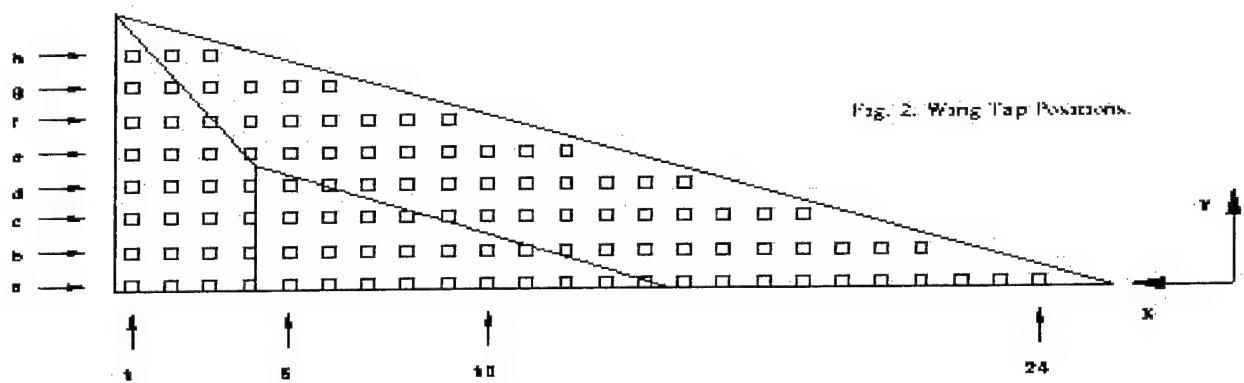


Fig. 2. Wing Tap Positions.

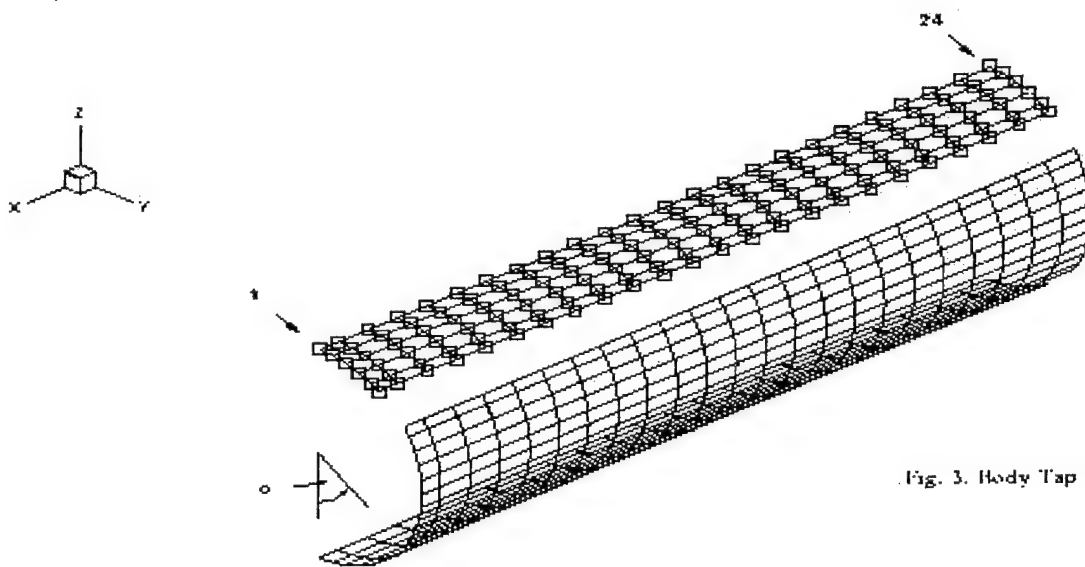


Fig. 3. Body Tap Positions.

Figure 3. Fin and Body Surface Pressure Measurement Layout.

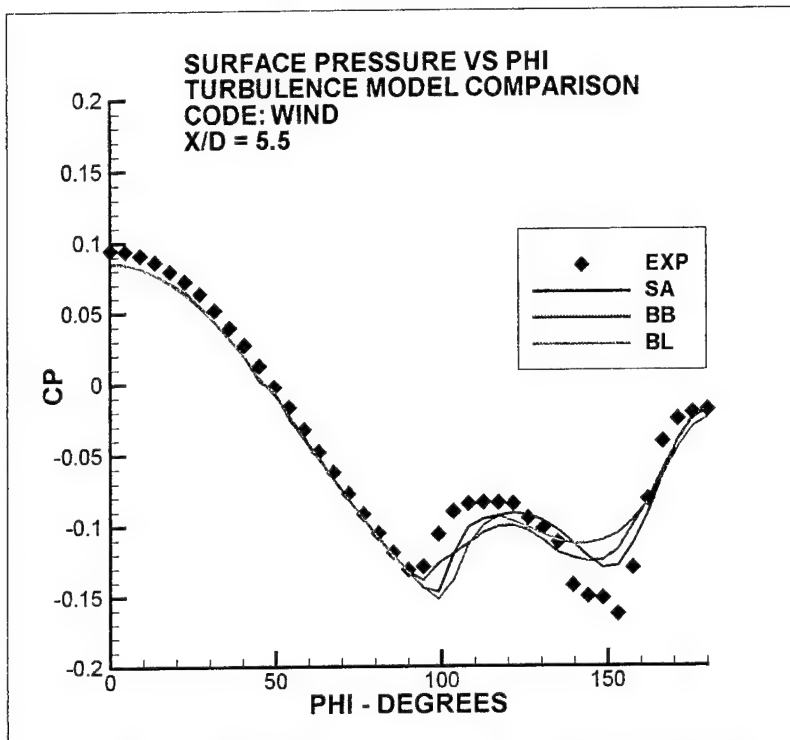


Figure 4. Body Surface Pressures vs Circumferential Position at  $X/D = 5.5$ , Computation Compared to Experimental Data,  $M = 2.5$ ,  $\alpha = 14^\circ$ .

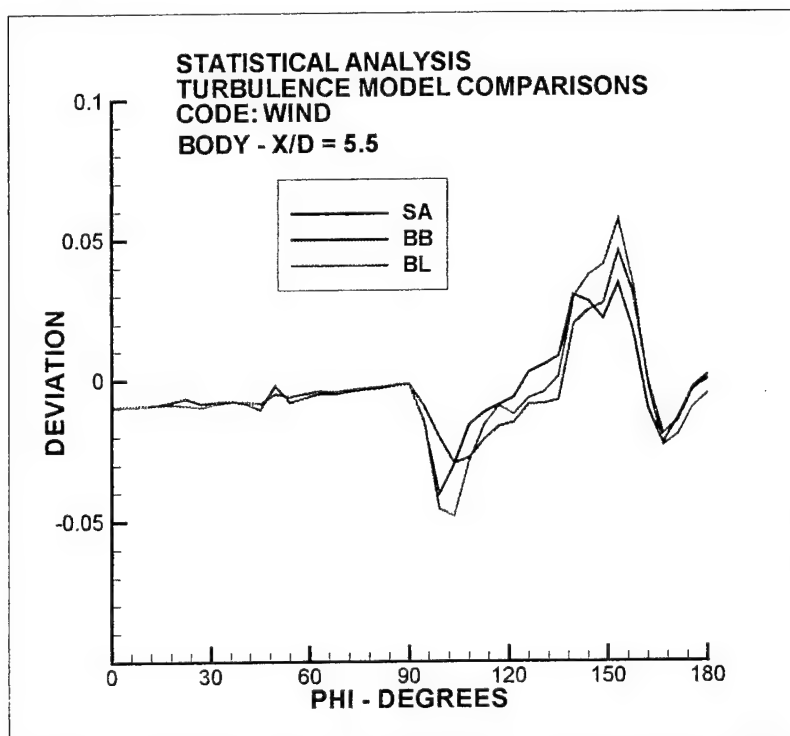


Figure 5. Deviation from Experiment vs. Circumferential Position,  $X/D = 5.5$  Roll = 0., Body Alone, Three Turbulence Models, Mach = 2.5,  $\alpha = 14^\circ$ .

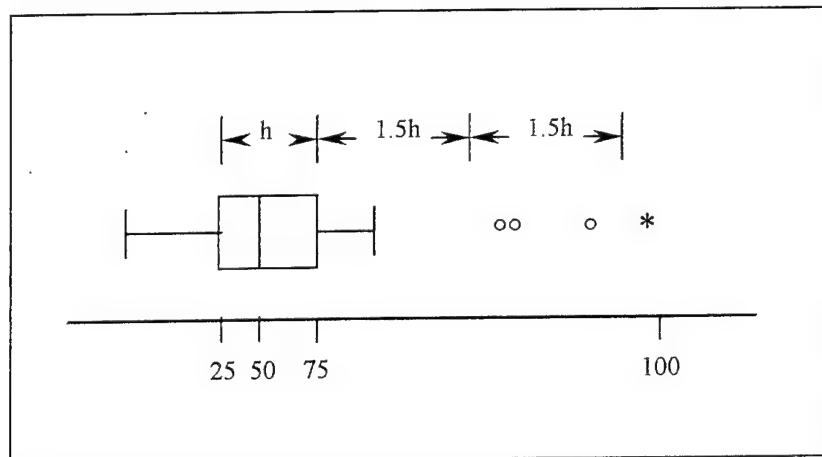


Figure 6. Box and Whisker Statistic Illustration

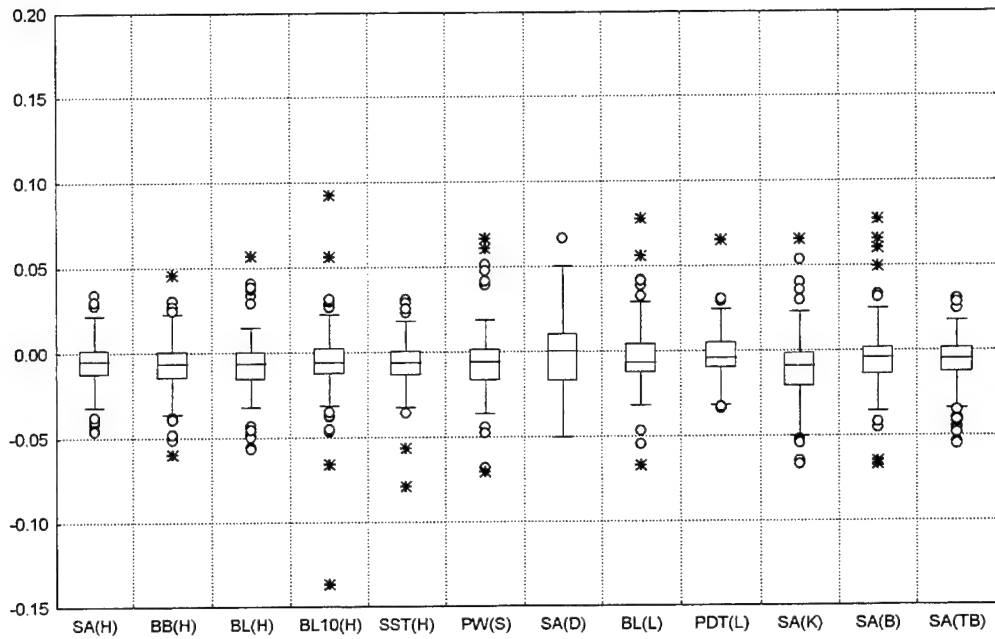


Figure 7a. Box and Whisker Plot, Body Surface Pressures, Roll = 0.

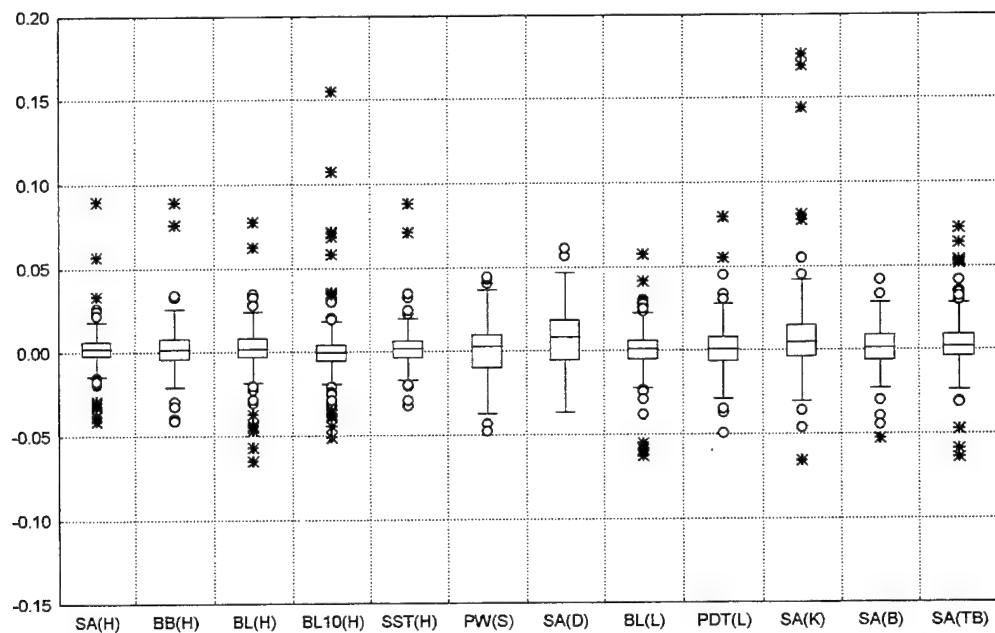


Figure 7b. Box and Whisker Plot, Fin Surface Pressures, Roll = 0.

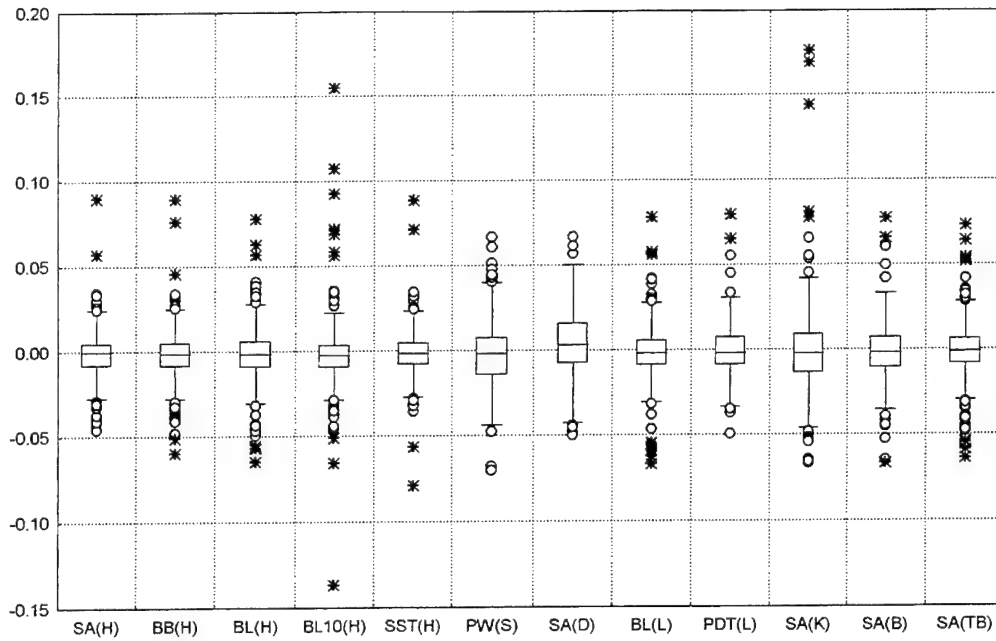


Figure 7c. Box and Whisker Plot, Body plus Fin Surface Pressures, Roll = 0.

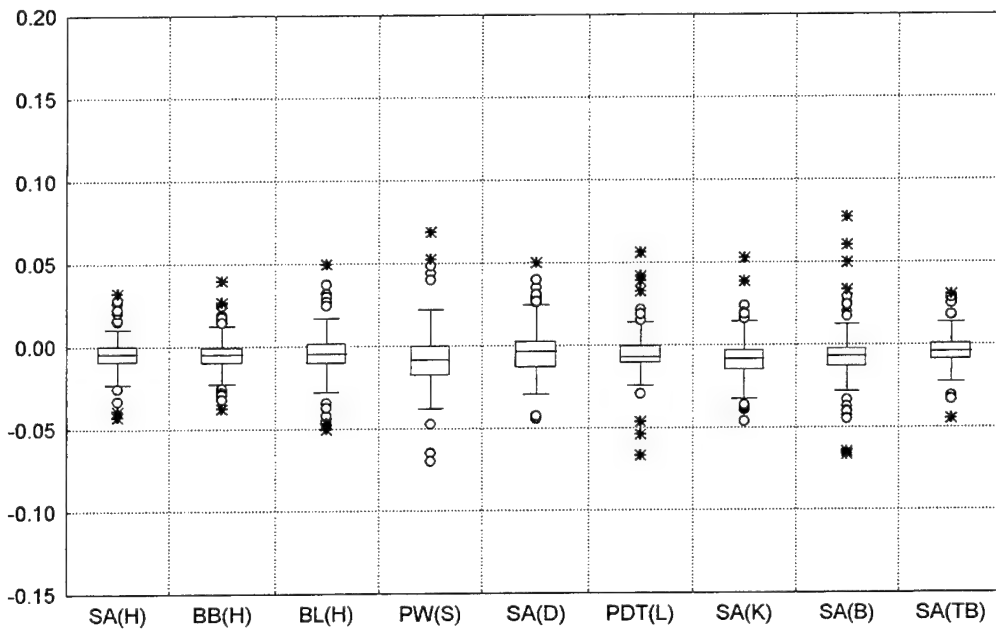


Figure 8a. Box and Whisker Plot, Body Surface Pressures, Roll = 45.



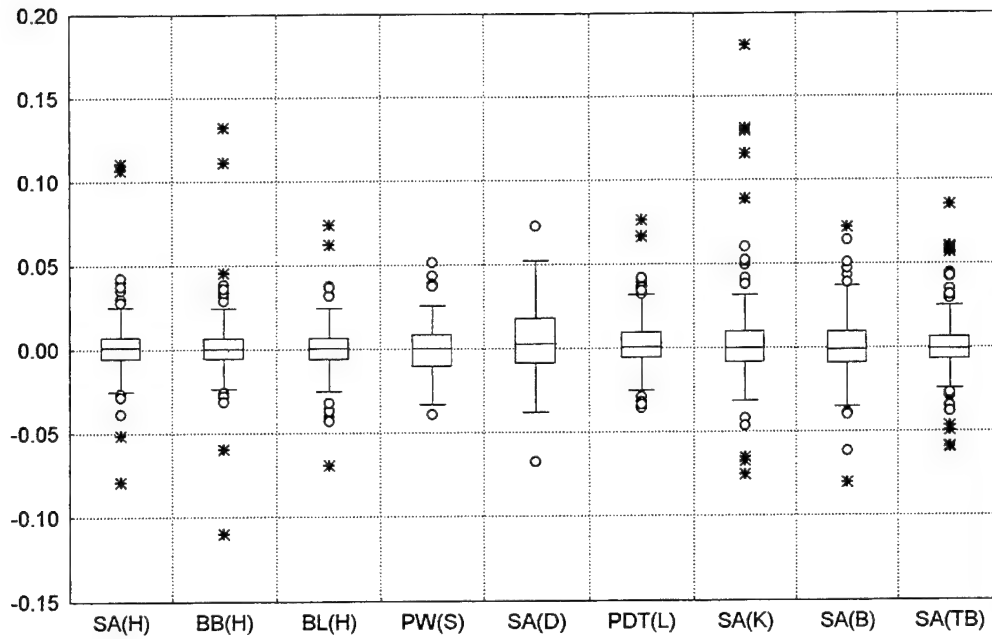


Figure 8b. Box and Whisker Plot, Fin Surface Pressures, Roll = 45.

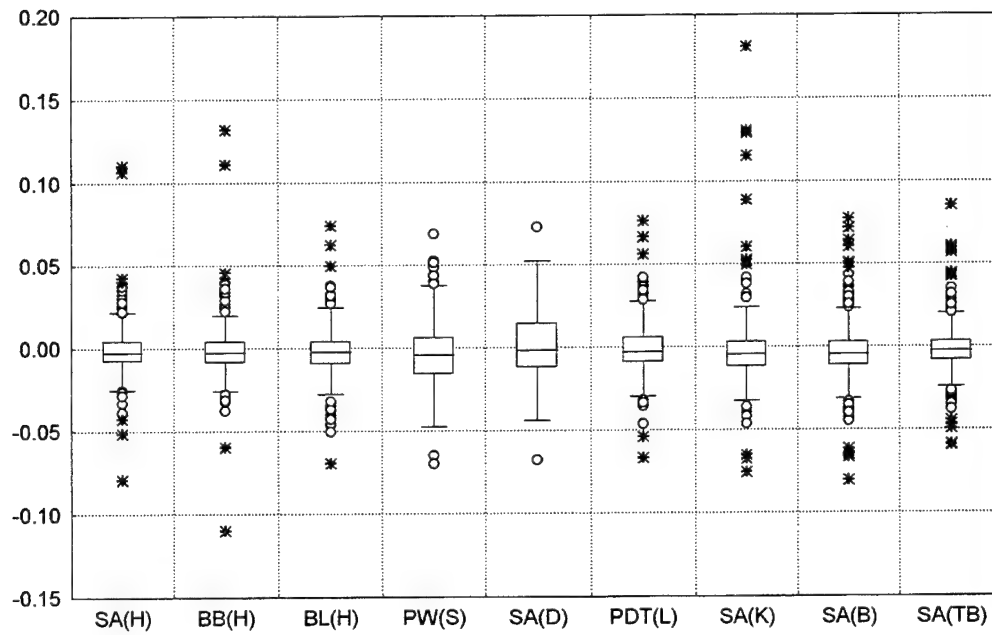


Figure 8c. Box and Whisker Plot, Body plus Fin Surface Pressures, Roll = 45.

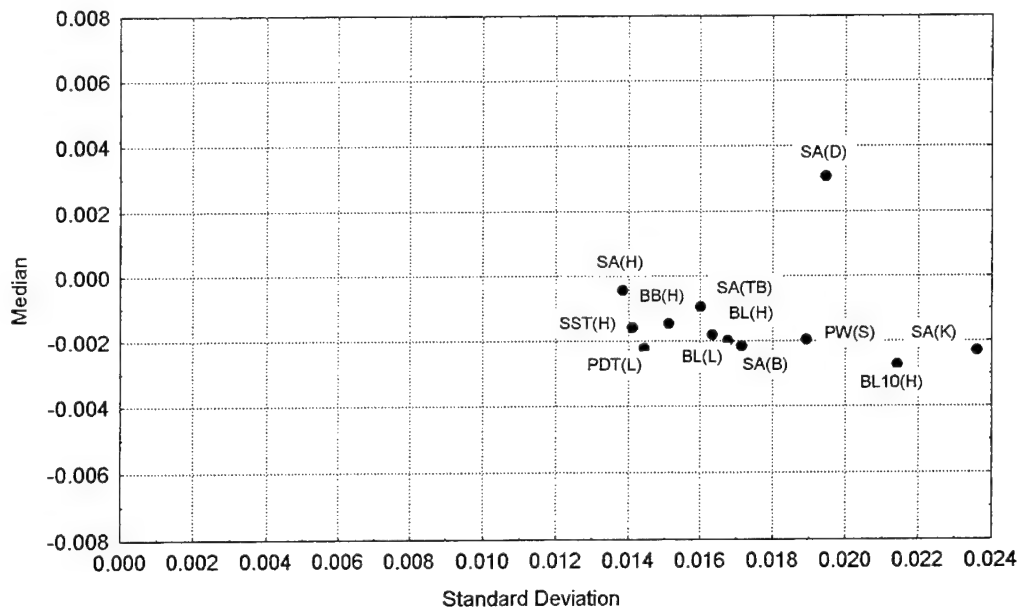


Figure 9a. Body plus Fins, Roll = 0, Standard Deviation vs Median.

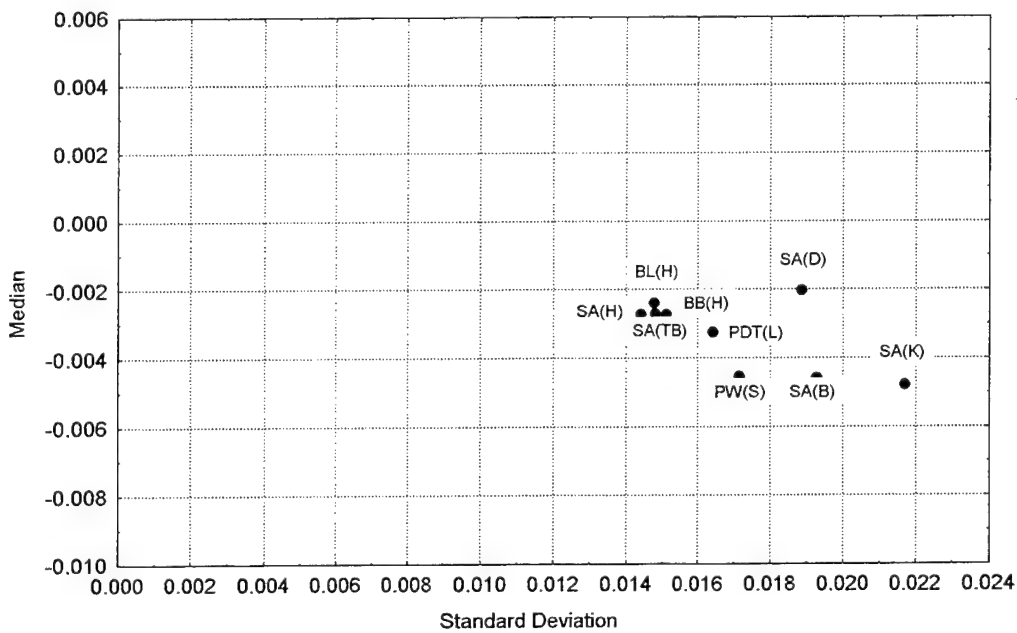


Figure 9b. Body plus Fins, Roll = 45, Standard Deviation vs Median.

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13. ABSTRACT(Maximum 200 words) <p>An international computational aerodynamics study under the auspices of The Technical Cooperation Program (TTCP) Weapons Technology Panel 2 (APN-TP-2) involving participants from defense research laboratories of the United States, United Kingdom, Canada, and Australia was recently completed. The purpose of this study was to examine computational predictive technologies for finned missile shapes by comparing Navier-Stokes predictions to experimental data. Experimental data consisting of surface pressures on the body and fins, flow field pitot pressures, and force measurements were available for comparison to the computational results. The computational results for this study established an extensive database for evaluation and comparison. The full database consists of results from six Navier-Stokes codes obtained by seven multi-block patched and unstructured grids for five distinct test cases. The statistical analysis techniques developed to help provide an evaluation of the predictive techniques are described. Quantitative results of the analysis of the differences between computational and experimental results are presented graphically and quantitatively in terms of medians, standard deviation, and a figure of merit to assist in the overall evaluation of the study results. The good performance achieved using the Spalart-Allmaras turbulence model and multi-block patched and unstructured grid techniques are noted in the findings.</p>				
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